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During the week of February 23, 1970, representatives of the Water Quality Office visited the Rocky Flats Plant of the Atomic Energy Commission (AEC). The purpose of the visit and the report was to obtain information on liquid radioactive waste management practices at the facility and the environmental surveillance activities in the plant environs.

The report presents the findings of the February investigation. The discussion of the environmental levels of plutonium is limited to soil, water, and bottom sediment.

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RADIOACTIVITY LEVELS IN THE ENVIRONS OF THE ROCKY FLATS PLUTONIUM PLANT

Golden, Colorado

1970

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ENVIRONMENTAL PROTECTION AGENCY
WATER QUALITY OFFICE
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Introduction and Background

During the week of February 23, 1970, representatives of the Water Quality Office visited the Rocky Flats Plant of the Atomic Energy Commission (AEC). Located approximately 21 miles northwest of Denver, Colorado, between Golden and Boulder, the facility is operated by the Dow Chemical Company under contract to the AEC. The purpose of the visit was to obtain information on liquid radioactive waste management practices at the facility and the environmental surveillance activities in the plant environs. Correspondingly, related discussions on the surveillance activities of the State of Colorado were held with personnel of the Department of Health, Division of Air, Occupational, and Radiation Hygiene.

The Water Quality Office was represented by Dr. Milton W. Lammering and Mr. Robert C. Scott, both of the Radiological Activities Section, Division of Technical Support, Cincinnati, Ohio, and Mr. Thomas M. Carter, Missouri Basin Region, Kansas City, Missouri. In the discussions with personnel of the AEC and Dow Chemical Company, Mr. A. Hazle represented the Colorado Department of Health, Division of Air, Occupational, and Radiation Hygiene.

Normal operation of the plant involving the production of plutonium parts for nuclear weapons results in the release of small quantities of plutonium to the environment via the liquid waste treatment system. In addition to this controlled and regulated release mode, accidental plutonium releases have occurred on three occasions: a) a major fire in 1957,

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b) leakage from a storage field of drums containing plutonium-contaminated oil (some time during 1955 through 1967), and c) a major fire on May 11, 1969. The last incident was the subject of a highly critical report[1] by the subcommittee of the Colorado Committee for Environmental Information. Following the release of the Committee's report, a rash of articles appeared in the local news media on the public health implications of the May 11 fire as well as the general threat to public health and safety posed by the continued operation of the plant. Although WQO involvement was in response to the publicized controversy surrounding the plant, the evaluation by WQO personnel was limited to a review of liquid radwaste management practices and a brief, but intensive, sampling program to determine plutonium levels in the watercourse crossing the plant boundary and nearby lakes and reservoirs. Evaluations of the probabilities of future fires, explosions, and criticality accidents at the plant and the health hazards associated with such incidents are beyond the realm of the vested responsibilities and authority of the Water Quality Office.

A previous Federal inspection of waste disposal practices at the Rocky Flats Plant was conducted on December 18, 1963, by Mr. Keith F. Chrisman, a sanitary engineer in Region VIII, Public Health Service, Department of Health, Education, and Welfare. In recommending no need for remedial action, it was noted that the Colorado State Department of Health had concluded that the facility was not a source of detrimental water pollution. The State's position has not changed in the intervening years.

The following sections of this report pertain to the findings of the February investigation. Therefore, discussion of the environmental levels of plutonium is limited to soil, water, and bottom sediment. A second report will cover the September 1970 study to determine the plutonium levels in the aquatic biota inhabiting Great Western Reservoir and Standley Lake and the general distribution of plutonium in the bottom sediment of Great Western Reservoir.

Liquid Waste Management Practices

All material in the liquid waste effluents from the Rocky Flats Plant ultimately reach Great Western Reservoir, a multiple-purpose reservoir with a maximum storage capacity in excess of 3100 acre-feet. Liquid radioactive wastes, after dilution with treated sanitary sewage, flow through a system of four small retention ponds connected in series. The overflow from this pond system flows down the south fork of Walnut Creek, and subsequently, into Great Western Reservoir (refer to Figure 1). The mouth of Walnut Creek is approximately four miles downstream from the outer plant boundary. Except during the spring melt, flow into Great Western Reservoir from Walnut Creek is comprised almost totally of liquid wastes from the plant. Great Western Reservoir is the public water supply source for the City of Broomfield.

On-site discharges of liquid radwastes are made at several buildings as indicated by the following list.

Building Identification Number	Major Activity Carried Out in the Building
444	Handling of uranium-contaminated material
771	Plutonium recovery
774	Treatment facility for liquid radwastes
776	Holding tanks for laundry wastes from Building 778 are located in this building
779	Laboratory
881	Handling of uranium-contaminated material
95	Treatment facility for sanitary wastes

The disposal of liquid radwastes from Buildings 444, 771, 776, 779, and 881 is based on the results of chemical analyses of each batch. Normally, wastes from Buildings 771 and 779 are discharged to the drainage ditch carrying wastes to the retention pond system at a point upstream from the sewage treatment plant discharge. Liquid wastes from Buildings 444, 776 (laundry wastes), and 881 are mixed with raw sewage and pass through the biological treatment process. If, however, analysis of the waste batch shows that a specific constituent(s) exceeds the concentration limit(s) for discharge without treatment, the batch is transferred to Building 774 for the required treatment. For laundry wastes, treatment is required if the following limits are not met:

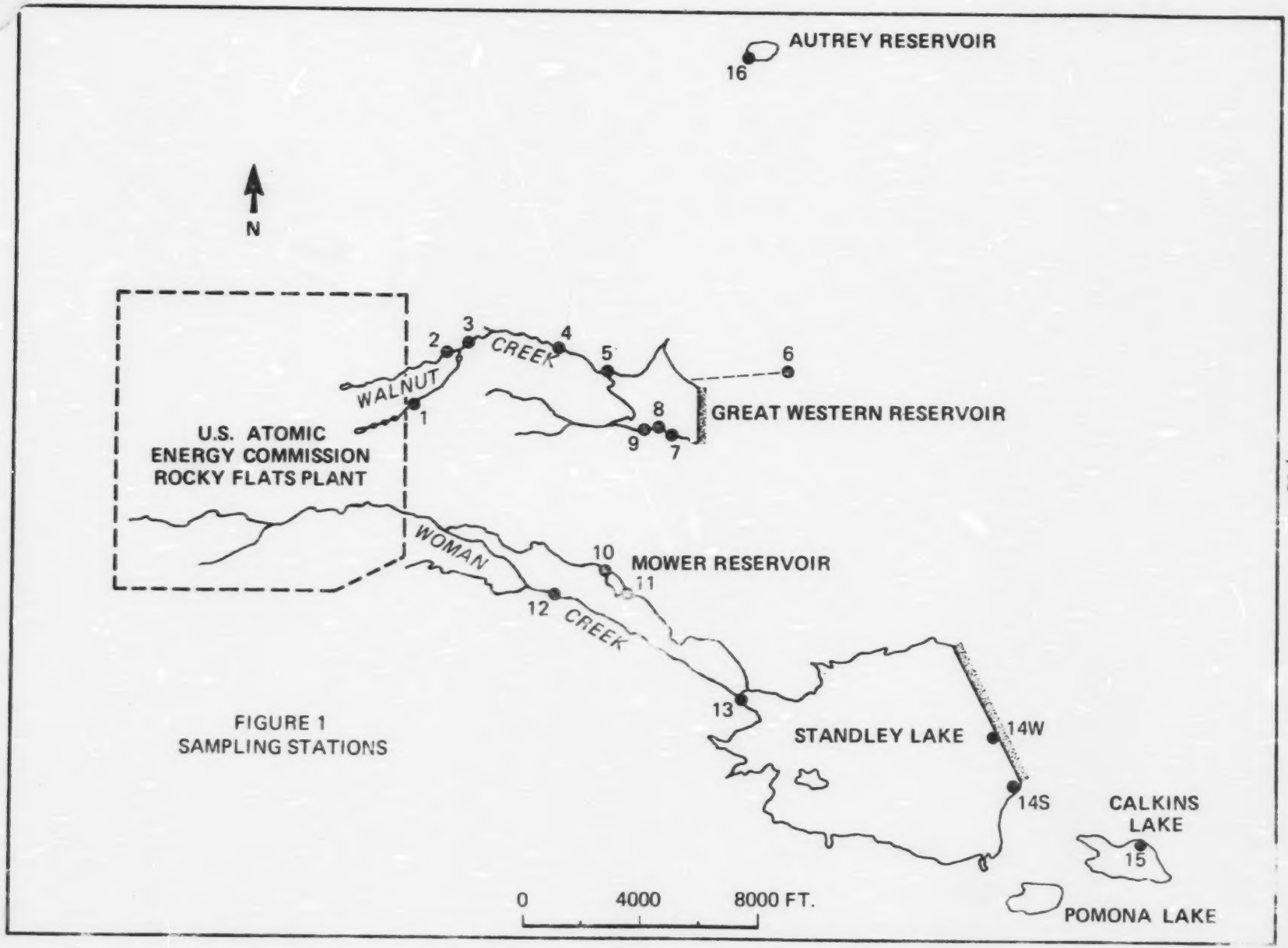

FIGURE 1
SAMPLING STATIONS

4a

Plutonium - 3500 dpm/l (approx. 1600 pCi/l)*

Nitrate ($NO_3^=$) - 45 mg/l

Hexavalent chromium - 1.0 mg/l

Concentration limits for treated waste discharges from Building 774, and presumably other buildings, are the same as those cited above for laundry wastes. Waste volumes discharged to the drainage ditch and the sewage treatment plant during the last half of 1969 and the corresponding amounts of gross alpha activity are listed in Table I.

Two basic processes are available for the treatment of liquid wastes: 1) chemical precipitation and sand filtration, and 2) evaporation with the water vapor vented to the atmosphere. As shown on the detailed process flow sheet (Appendix A), flexibility of operation exists within and between the two processes. In general, wastes classified as "high radioactivity - low nitrate" wastes are processed by chemical precipitation and filtration, analyzed on a batch basis, and discharged to the drainage ditch upstream from the sewage treatment plant. "High nitrate" wastes are evaporated. However, due to the limited capacity of the evaporator, high nitrate wastes are stored initially in a series of three asphalt-lined evaporation ponds for volume reduction. Evaporative losses have been sufficiently great to prevent a continuing increase in the volume of stored waste. Sludge produced in the

---

* About one-third of the effluent limit for dissolved plutonium-239 as specified in 10CFR20, Appendix B, Table II. Assuming the plutonium is totally in solution is conservative since the corresponding limit for insoluble plutonium is 30,000 pCi/l.

Table I

Liquid Radioactive Waste Disposal - July through December 1969

Source	Volume (gallons)	Gross Alpha Radioactivity (curies)
To drainage ditch from:		
Building 771	23,000	1.3×10^{-4}
Building 774	1,117,600	1.4×10^{-3}
Building 779	91,400	9.1×10^{-5}
To sewage treatment plant from:		
Building 444	146,500	1.9×10^{-3}
Building 776	1,137,200	5.4×10^{-3}
Building 881	261,400	2.4×10^{-3}

decontamination of liquid radwastes is drummed for off-site burial at the National Reactor Testing Station (Idaho).

The sewage treatment plant is an extended aeration facility with a chlorinated effluent. Although the purpose of the plant is the treatment of non-radioactive sanitary wastes, some degree of decontamination of the radwastes from Buildings 444, 776, and 881 is also achieved by the treatment process. The uranium-contaminated sludge from the digester is buried in an on-site landfill unless established radioactivity limits are exceeded. In the latter case, the sludge is drummed for shipment to the National Reactor Testing Station. The plant effluent also has a dilution effect on wastes discharged to the drainage ditch from Buildings 771, 774, and 779.

Although the system of ponds receiving the combined plant effluent was designed to provide retention of liquid wastes before entry into the unrestricted environment, the ponds also function as a series of oxidation ponds providing additional treatment of the organic-bearing wastes. Similarly, the luxurious algal growths undoubtedly produce additional decontamination of the plant wastes. However, this reduction in the amount of radioactivity released to the environment will not be realized on a long-term basis if the ponds are scoured during periods of high run-off. The effluent from the pond system is sampled proportional to flow and composited for analysis (gross alpha, nitrate, phosphate, fluoride, and hexavalent chromium). Gross alpha activity in the effluent is usually on the order of 15 pCi/l which by inference indicates that plutonium releases are

well below the operational limit of 1600 pCi/l.[2] Phosphate concentration data for 1969 were as follows:

Maximum - 38 mg/l as $PO_4^{\equiv}$

Minimum - 0.4 mg/l

Average - 8.9 mg/l

Due to decontamination in the sewage treatment plant and retention ponds, the net release of gross alpha activity to Walnut Creek during the last half of 1969 should have been less than the total of 11.3×10^{-3} curies shown in Table I.

Environmental Surveillance

Monitoring of environmental radioactivity levels in the environs of the Rocky Flats Plant is conducted routinely by personnel of the Dow Chemical Company. Based on the semi-annual monitoring reports published in the U. S. Public Health Service periodical, "Radiological Health Data and Reports," the operational details of the surveillance program are the following:

Type of Sample	Description
Air	Continuous air samples are collected at Coal Creek Canyon, Marshall, Boulder, LaFayette, Broomfield, Wagner School, Golden, Denver, and Westminster. Analyses of monthly composite samples are reported as a single average concentration for all stations.
Water	Except during winter months, monthly samples are collected from Baseline Reservoir, Great Western Reservoir, Standley Lake, and Ralston Reservoir.
Vegetation	Semi-annual collection; i.e., during one month of each six month reporting period. Samples are analyzed in accordance with two collection zones; less than four miles from the plant and four to eighteen miles from the plant.

Apparently topsoil sampling has been added to the surveillance program since the May 11 fire. Samples are analyzed for gross alpha activity which includes naturally-occurring radionuclides (uranium, thorium, radium, etc.) as well as any plutonium that might be present as a result of plant operation and/or atmospheric fallout.

The results of the monitoring program for 1968 and the first half of 1969 are shown in Table II. These data do not show any significant increases in gross alpha levels above natural background in the media sampled as the result of plant operations (including accidental releases). Since there is no information to indicate otherwise, it is assumed that the gross alpha results for water samples are representative of total activity (suspended plus dissolved).

The State of Colorado Department of Health routinely samples Walnut Creek at Indiana Street (just upstream from the mouth) on a weekly basis for gross alpha activity analysis. If the gross alpha activity is unusually high, a portion of the sample is sent to the Public Health Service Southwest Radiological Health Laboratory for plutonium analysis.

In addition to the routine surveillance programs carried out by Dow Chemical Company and the State Health Department, intensified monitoring was undertaken following the May 11 fire. During May and June 1969 Dow Chemical Company reported the collection and analysis of 52 additional water samples from the routinely sampled reservoirs.[3] The Denver Post in an editorial dated February 12, 1970, reported that the State Health Department collected 370 air samples and 94 water samples in the vicinity of the plant in the

Table II

Gross Alpha Activities in the Environs of the Rocky Flats Plant

Composite Air Samples ($pCi/M^3 \times 10^{-2}$)

1968	January	0.3	1968	July	0.5	1969	January	0.5
	February	2.2		August	0.5		February	0.4
	March	0.5		September	0.6		March	0.2
	April	0.5		October	0.7		April	0.3
	May	0.3		November	0.4		May	0.3
	June	0.7		December	0.7		June	0.3

Grab Water Samples (pCi/l)

	Jan.-June 1968	July-Dec. 1968	Jan.-June 1969
Great Western Reservoir	2.3	1.4	1.4
Standley Reservoir	1.3	1.5	1.5
Baseline Reservoir (7 miles north of site)	1.2	0.9	0.9
Ralston Reservoir	4.2	2.8	2.8

Vegetation (pCi/kg)

October 1967	
< 3 miles	120 (21)*
3-18 miles	118 (40)
October 1968	
< 4 miles	90 (62)
4-18 miles	96 (44)
May 1969	
< 4 miles	84 (39)
4-18 miles	77 (20)

* Number in parentheses denotes number of analyses.

Source: References 3, 4, and 5.

time period extending from one day after the fire through October 1969. The State Health Department also conducted an extensive soil and bottom sediment sampling program in February 1970. Soil samples were collected in the area around the plant up to a maximum radial distance of six miles. Bottom sediment samples were collected from Walnut Creek, Woman Creek, Great Western Reservoir, Mower Reservoir, Standley Lake, and Ralston Reservoir. Analyses for strontium-89 and 90 and plutonium-239 were performed by the Public Health Service Southwest Radiological Health Laboratory (Appendix B).

Following the May 11 fire, members of the Colorado Committee for Environmental Information also undertook a limited program to determine plutonium levels in Colorado eastern slope soils and at locations in the vicinity of the Rocky Flats Plant. In addition to the soil samples, water and bottom sediment samples were collected from Walnut Creek, Great Western Reservoir, Calkins Lake, Ralston Reservoir, and three more distant lakes: Boulder Reservoir (northeast of Boulder), Dodd's Lake (northeast of Boulder), and Boyd Lake (Loveland, Colorado). Based on the results obtained for the soil samples, it was concluded "that curies to tens of curies of plutonium from the Rocky Flats Plant have been deposited in off-site areas." This is in contrast to the estimate of 0.3 curie by the State of Colorado Department of Health (Appendix B).

Water Quality Office Study

Sampling Procedures

Environmental samples were collected on February 25 and 26, 1970 by Water Quality personnel with assistance from Mr. A. Hazle, Colorado Department of

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Health. The types of samples consisted of water samples, bottom sediment samples, and filter sand and clarifier underflow samples from the Broomfield Water Treatment Plant.

Sampling station locations for water and bottom sediment samples are presented in Table III and Figure 1. Bottom sediment samples were collected by scraping the bottom area below the water line with a hand trowel. By using this procedure, each sediment sample was representative of the bottom most readily available for physical and chemical reactions with dissolved constituents in the water and recently deposited material. Grab samples of water were collected in one gallon plastic containers; 2 to 5 gallons per sample.

Soil samples (top 1/4" - 1/8" of soil) were collected with a hand trowel at three locations:

1. Ungrazed area near the southeast corner of Great Western Reservoir, west of the service road.
2. Approximately 50 feet southeast of the road culvert conveying Woman Creek under Indiana Street. Area has been grazed in the past.
3. North side of Calkins Lake, about 300 feet east of the water intake station (grazed field).

The sampling site near Great Western Reservoir was in the general area of the location at which the Colorado Committee for Environmental Information observed the maximum plutonium-239 concentration in soil.

Filter sand samples, before and after backwashing, and a sample of the clarifier underflow were collected at the Broomfield Water Treatment Plant. The filter sand samples were collected by scraping the surface of the sand bed with a hand trowel. The sample collected at the termination of the filter run was a mixture of "scum" and filter sand (white); the scum representing alum floc carried over from the clarifier. Clarifier underflow, a heavy slurry, was the product of alum coagulation of Great Western Reservoir water. Due to maintenance work on one of the two treatment circuits, the 5 MGD plant was hydraulically overloaded at the time of sample collection. Raw water chemical dosages were 50 mg/l alum, 20 mg/l soda ash, 1.0 mg/l activated carbon, and 0.5 mg/l Palmer coagulant (product of the Calgon Corporation).[6]

Analytical Procedures

The analytical procedures for determining gross alpha radioactivity, total alpha radium, uranium, plutonium, strontium-89 and 90, and tritium concentrations in the various environmental samples are described in detail in Appendix C. Pretreatment of water samples consisted of filtration through a membrane filter of 0.45 micron porosity. Sediment and soil samples were dried at 103°C and ground to pass a No. 100 mesh sieve before specific analyses were initiated.

Since the analytical procedure for plutonium determines "total" plutonium, the individual results represent the contributions of plutonium-238 and 239; not plutonium-239 alone. By virtue of their widespread occurrence in the atmosphere, both isotopes of plutonium were probably present in

Table III

Sampling Stations

Station Number	Description (Date of Collection)	Type
1	South fork of Walnut Creek at site boundary (2/25/70)	Water, Bottom Sediment
2	Middle fork of Walnut Creek; 50 feet upstream from confluence with north fork (2/25/70)	Water, Bottom Sediment
3	Main stem of Walnut Creek; 50 feet downstream from confluence of south fork with middle and north forks (2/25/70)	Bottom Sediment
4	Walnut Creek at Indiana Street (2/25/70) (a) East side of culvert (b) West side of culvert at edge of small pond	 Water Bottom Sediment
5	Great Western Reservoir at mouth of Walnut Creek (2/25/70)	Bottom Sediment
6	Great Western Reservoir; east end - raw water sample collected at Broomfield Water Treatment Plant (2/25/70)	Water
7	Great Western Reservoir; south shore - composite sample collected along approximately one-half mile of shoreline extending from the dam (2/25/70)	Bottom Sediment
8	Great Western Reservoir; south shore - composite sample collected along a 25 foot strip in 2 to 5 inches of water (2/26/70)	Bottom Sediment
9	Great Western Reservoir; south shore - discrete sample collected above water line from wave-deposited (or reworked) sediments (2/26/70)	Bottom Sediment
10	Mower Reservoir at mouth of diversion ditch; west end (2/26/70)	Bottom Sediment

(continued)

Table III (continued)

Sampling Stations

Station Number	Description (Date of Collection)	Type
11	Mower Reservoir; east end at dam (2/25/70)	Water, Bottom Sediment
12	Woman Creek at Indiana Street (2/26/70)	
	(a) Small pond east of the road culvert	Water
	(b) Channel downstream from pond	Bottom Sediment
13	Standley Lake near mouth of Woman Creek (2/26/70)	Bottom Sediment
14	Standley Lake; east end (2/26/70)	
	(a) Center of dam near pumping station	Water
	(b) Southwest of dam along a 25 foot edge of shoreline in zone of heavy wave action	Bottom Sediment
15	Calkins Lake; north side (2/26/70)	Water, Bottom Sediment
16	Autrey Reservoir (approximately 4 miles northeast of the plant; Boulder County) (2/25/70)	Water, Bottom Sediment

the samples collected in the environs of the Rocky Flats Plant. However, the bulk of the plutonium in each case was probably attributable to plutonium-239. This conclusion is based on the plutonium monitoring of airborne particulates and precipitation by the U. S. Public Health Service. During 1969 the data for the Denver sampling station showed plutonium-239 concentrations to be several times higher than the corresponding plutonium-238 concentrations. Although the ability to differentiate between plutonium-238 and 239 is of interest from the standpoint of analytical precision, it is of academic importance in respect to evaluating the environmental impact of plutonium-239 emissions from the Rocky Flats Plant. Total plutonium is an adequate parameter for such an evaluation since the effects of plant emissions are based on increases above baseline values (plutonium attributable to atmospheric fallout).

Results

Physical and radiological data for the water samples collected during the February 1970 study are tabulated in Tables IV and V. The presence of tritium (H-3), strontium-89 and 90, and radium (total alpha) in the samples is attributable to natural sources and/or atmospheric fallout from nuclear weapons tests; not waste releases (scheduled or accidental) from the Rocky Flats Plant. The average dissolved concentrations of these radionuclides were 1340 pCi/l of tritium, < 0.1 pCi/l of strontium-89, 1.2 pCi/l of strontium-90, and < 0.1 pCi/l of total alpha radium.

Assuming the accidental releases of plutonium from the Rocky Flats Plant have not caused measurable increases in the levels of dissolved

Table IV

Solids Concentrations in Water Samples

Station	Solids Concentration (mg/l) Suspended	Dissolved
Walnut Creek:		
South fork at site boundary (No. 1)	13	150
Middle fork (No. 2)	4	220
Indiana Street (No. 4)	12	250
Great Western Reservoir (No. 6)	4	130
Mower Reservoir (No. 11)	17	110
Woman Creek (No. 12)	< 1	150
Standley Lake (No. 14)	5	120
Calkins Lake (No. 15)	16	80
Autrey Reservoir (No. 16)	13	220

Table V

Dissolved Radioactivity in Water Samples

Station	Dissolved Radioactivity (pCi/l)[a]						
	Gross Alpha	Tritium	Sr-89	Sr-90	Total Alpha Radium	Uranium	Plutonium-239
Walnut Creek:							
South fork at site boundary (No. 1)	N.D.	N.D.	0	0.6	0.1	7.9	0.04
Middle fork (No. 2)	0.9	N.D.	0.1	0.7	< 0.1	2.7	0.02
Indiana Street (No. 4)	0.6	N.D.	0.1	0.6	< 0.1	4.8	0.05
Great Western Reservoir (No. 6)	0.8	1340	0	1.4	0.1	2.6	0.03
Mower Reservoir (No. 11)	0.8	1050	0	1.8	0.1	1.1	< 0.02
Woman Creek (No. 12)	0.9	N.D.	0.5	0.4	< 0.1	2.2	< 0.02
Standley Lake (No. 14)	0.5	1390	0	0.6	< 0.1	2.4	< 0.02
Calkins Lake (No. 15)	0.5	1550	0	2.2	0.2	2.7	0.03
Autrey Reservoir (No. 16)	0.8	1390	0	2.1	< 0.1	0.5	< 0.02

(a) Uranium in µg/l

N.D. - Not determined

plutonium in Autrey Reservoir, Calkins Lake, and Standley Lake, the apparent "baseline" concentration for dissolved plutonium from the uncontrollable source, atmospheric fallout, was ≦ 0.03 pCi/l at the time of sampling. As shown in Table V and Figure 2, only the samples from Walnut Creek (Stations Nos. 1 and 4) exhibited slightly higher concentrations - 0.04 and 0.05 pCi/l, respectively. Similarly, these same two stations on Walnut Creek were the only locations at which the dissolved uranium concentration exceeded the average area background concentration of approximately 2 μg/l. The sample of raw water from the east end of Great Western Reservoir (Station No. 6) did not indicate any increased level of uranium and/or plutonium contamination as the result of liquid waste discharges to Walnut Creek.

For comparative purposes, the plutonium-239 results for water samples reported by the Colorado Committee for Environmental Information[4] are summarized below. It is assumed that the samples were collected during August 1969.

Location	Plutonium-239 (pCi/l)
Walnut Creek - Roadside pond at Indiana Street	0.19
Great Western Reservoir	0.10
Ralston Reservoir	0.01
Calkins Lake	0.01

These data agree favorably with the corresponding results from the February study. The substantially higher concentration in Walnut Creek is not unusual or unexpected considering probable differences in flow conditions

and the batch nature of liquid waste discharges. What does appear to be a significant difference is the concentration reported for Great Western Reservoir which would be indicative of measurable contamination in the reservoir as the result of plant wastes. However, the discussion of the results in their report indicates that this station was actually located in or near the mouth of Walnut Creek:

> " ... The highest Pu^{239} concentrations observed are those for Great Western Reservoir and the small roadside pond, both on Walnut Creek ... "

Thus, this particular sample was apparently not representative of general water quality in Great Western Reservoir.

The radioactivity data for bottom sediment samples are presented in Table VI. Average concentrations of strontium-89, strontium-90, and total alpha radium in all sediment samples were < 0.5, 0.1, and 4.9 pCi per gram dry weight, respectively. For all stations, except those on Walnut Creek, the uranium concentrations ranged from 0.4 to 2.8 µg per gram dry weight; averaging 1.0 µg/gram. Considering these values and the result for the middle fork sample, no significant accumulation attributable to the discharge of uranium-bearing liquid wastes was observed in the Walnut Creek samples. Excluding the station on the middle fork, the average uranium concentration for Walnut Creek sediments was 1.5 µg/gram. The average concentration for plutonium-239 at baseline locations (Autrey Reservoir, Standley Lake, and Calkins Lake) was 0.05 pCi per gram dry weight. This baseline concentration is comparable to the concentrations reported by the Colorado Committee for Environmental Information[1] and the State of Colorado (Appendix B) for

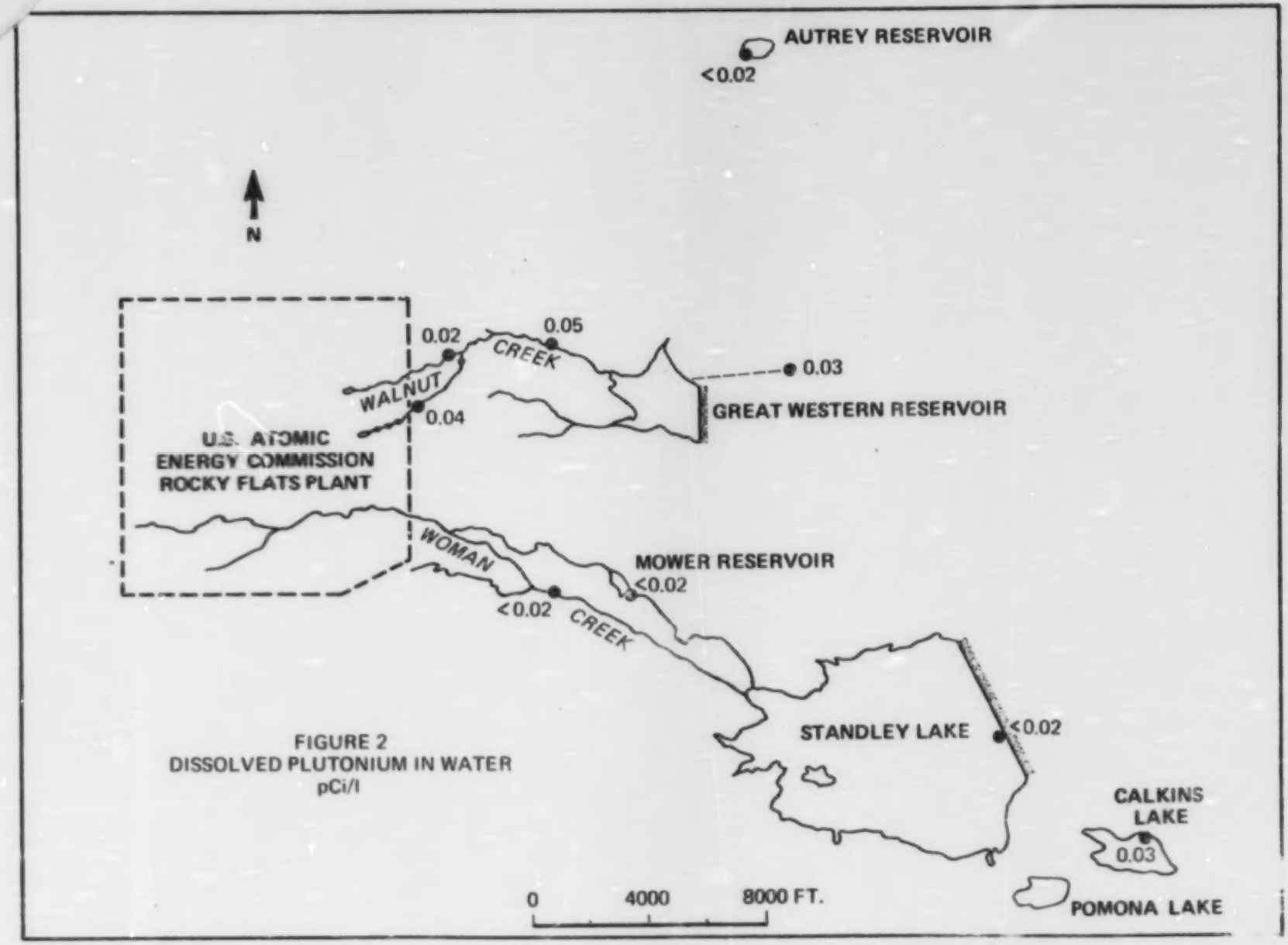

FIGURE 2
DISSOLVED PLUTONIUM IN WATER
pCi/l

202

sediments from Standley Lake, Calkins Lake, and Ralston Reservoir - average of 0.07 pCi/gram dry weight with a range of 0.01 to 0.18.

Accumulation of plutonium from liquid waste discharges was observed in sediment collected from the middle fork and main stem of Walnut Creek. As shown in Table VI and Figure 3, plutonium concentrations in Walnut Creek ranged from a maximum 3.5 pCi/gram just below the plant boundary to less than 2 pCi/gram in the lower reach of the main stem (Indiana Street to the mouth). In comparison to the observed level of contamination (4 to 7X baseline), similar results obtained by the State of Colorado indicated a substantially higher level of contamination. These data corresponding to the collection date of February 18, 1970, were as follows:

Location	Plutonium-239 (pCi/gram dry weight)
Upper south Walnut Creek	21
Walnut Creek	49
Pond; Walnut Creek at Indiana Street	13

Since flushing of the creek by heavy runoff did not occur in the week between the collection dates, the only reasonable explanations for the apparently different sets of findings are differences in the hydrological characteristics of the sampling locations (pool versus riffle or a combination thereof) and sampling techniques (thickness of the scraped layer, heterogeneity of sample composition, etc). For example, considerable variation would be expected for samples collected from the pond at Indiana Street

Table VI

Radioactivity in Bottom Sediment Samples

Station	Radioactivity Concentration (pCi/gram dry weight)[a]				
	Gross Alpha	Strontium-90	Total Alpha Radium	Uranium	Plutonium-239
Walnut Creek:					
South fork at site boundary (No. 1)	18	0.1	3.4	1.1	3.51
Middle fork (No. 2)	10	0.1	5.4	2.3	0.50
Main stem, below confluence with middle fork (No. 3)	17	0	2.8	1.0	3.41
Indiana Street (No. 4)	14	0.1	4.1	2.1	0.92
At the mouth (No. 5)	13	0.3	6.3	1.9	1.75
Great Western Reservoir:					
South shore near dam (composite)(No. 7)	7	0.2	5.4	1.3	0.10
South shore (composite) (No. 8)	12	0	6.3	0.4	0.11
South shore (discrete sample)(No. 9)	12	0.2	6.6	2.8	0.13
Mower Reservoir:					
West end (No. 10)	11	0	4.3	0.5	0.10
East end (No. 11)	13	0.1	3.3	0.4	0.09
Woman Creek (No. 12)	9	0	4.8	1.5	0.23

(continued)

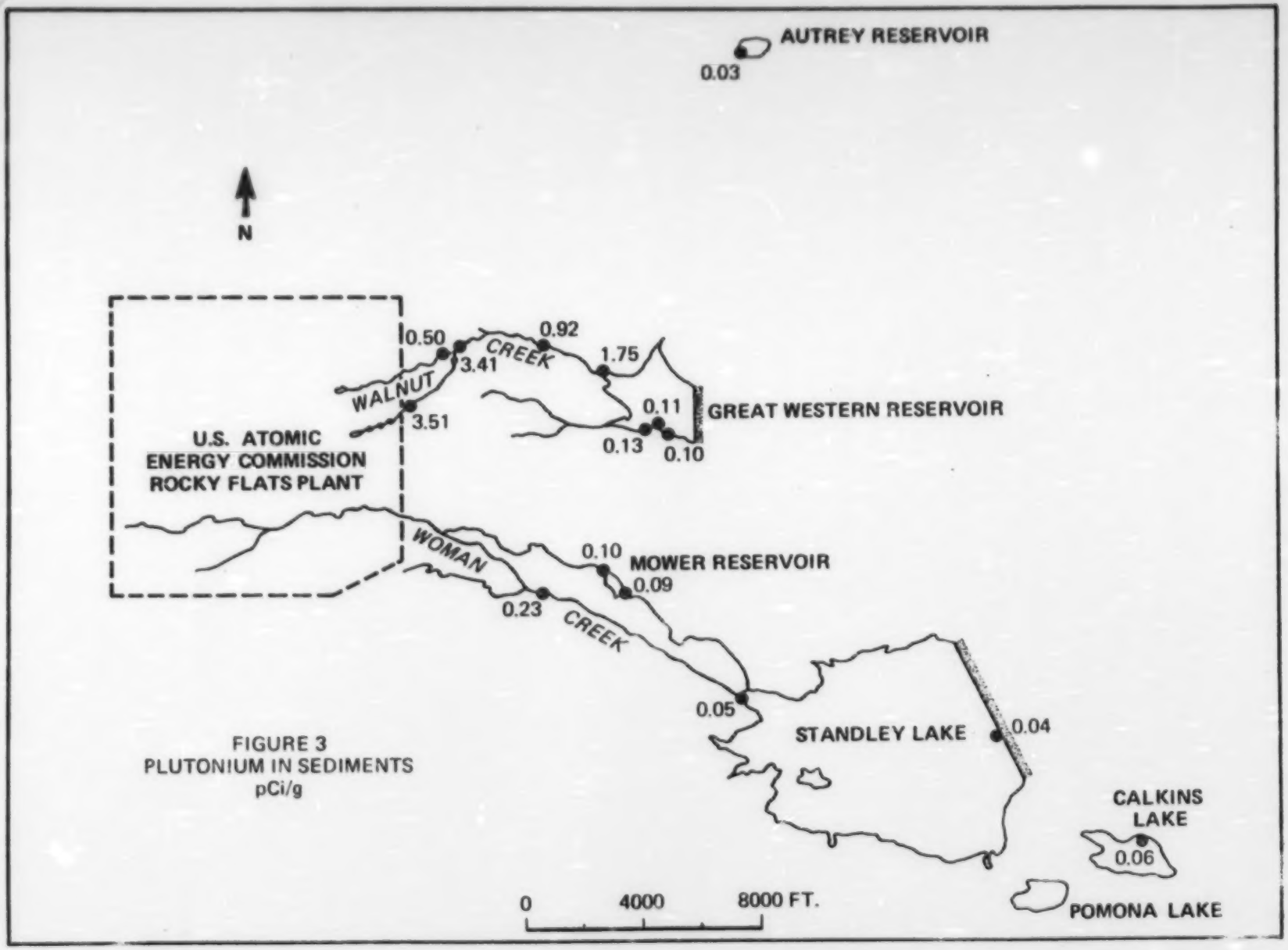

FIGURE 3
PLUTONIUM IN SEDIMENTS
pCi/g

22a

Table VI (continued)

Radioactivity in Bottom Sediment Samples

Station	Radioactivity Concentration (pCi/gram dry weight)[a]				
	Gross Alpha	Strontium-90	Total Alpha Radium	Uranium	Plutonium-239
Standley Lake:					
Near mouth of Woman Creek (No. 13)	10	0.2	12.5	0.6	0.05
East end (No. 14)	8	0	0.7	0.6	0.04
Calkins Lake (No. 15)	7	0	4.3	0.7	0.06
Autrey Reservoir (No. 16)	8	0.2	3.2	0.7	0.03

(a) Uranium in μg/gram

Strontium-89 less than 0.5 pCi/gram in each case.

depending on whether the samples are collected near the head end of the pond, the center, or just below the waterline along the periphery of the pond. The contamination observed in sediment from the middle fork of Walnut Creek and Woman Creek (at Indiana Street) was probably caused by wind transport and/or surface runoff of plutonium-contaminated soil. The State of Colorado also observed contamination in Woman Creek - 1.0 pCi/gram for a sample collected on February 18, 1970.

Although certainly not conclusive, the sediment samples from Mower Reservoir and Great Western Reservoir indicated measurable, albeit slight, accumulation of plutonium as the result of accidental airborne releases from the plant. The discharge of plutonium-bearing liquid wastes was not considered a causative source since the samples from Great Western Reservoir were collected at locations wherein the ultimate deposition of sediment from Walnut Creek would be most unlikely. Actually, these sediment samples should be considered representative only of shallow, shoreline conditions and not the general bottom condition in the respective reservoirs. Assuming the bottom materials in these shallow areas were similar to nearby topsoils as regards plutonium content, the suggested possibility of accumulation above baseline values in the shoreline sediments is not completely implausible. Both reservoirs are within sectors characterized by "elevated" levels of plutonium in soil (Appendix B).

The clarifier underflow sample from the Broomfield Water Treatment Plant showed that the treatment process produced a finished water of lower uranium and plutonium concentrations than the raw water. On a dry weight

basis, the alum sludge contained the maximum concentration of uranium among all the samples analyzed; the plutonium concentration was of the same magnitude as that observed for Walnut Creek sediment samples (Table VII). Carryover of the floc to the sand filter was shown by the uranium and plutonium content of the filter sand samples collected before and after backwashing.

Plutonium levels observed in the three soil samples are summarized in Table VIII, and are consistent with similar findings of the State of Colorado and the Colorado Committee for Environmental Information.

Spearman rank-order correlations were performed between the gross alpha and uranium, total alpha radium, and plutonium results, respectively, for sediment and soil samples. Interestingly, there was no correlation between gross alpha and uranium or gross alpha and total radium, but a significant correlation between gross alpha and plutonium results at the 1% confidence level. Despite this relationship, gross alpha measurements alone are not adequate for assessing the environmental impact of plutonium releases (accidental or scheduled) from the plant. Although the gross alpha analysis is responsive to substantial increases in plutonium levels, it lacks sufficient precision for detecting the small subtle changes which have occurred in the environs of the Rocky Flats Plant.

Table VII

Broomfield Water Treatment Plant Samples

Sample Description	Radioactivity Concentration (pCi/gram dry weight)[a]				
	Gross Alpha	Strontium-90	Total Alpha Radium	Uranium	Plutonium-239
Clarifier underflow (alum sludge)	34	1.2	3.1	57.5	1.42
Filter sand:					
Before backwash	12	0.3	3.0	20	0.16
After backwash	4	0	0.3	0.2	0.04

(a) Uranium in µg/gram

Table VIII

Radioactivity in Soil Samples

Location	Radioactivity Concentration (pCi/gram dry weight)[a]					
	Gross Alpha	Strontium-89	Strontium-90	Total Alpha Radium	Uranium	Plutonium-239
Ungrazed area near the southeast corner of Great Western Reservoir.(NE 1/4 Sec. 7, T.2S.,R.69W.)	12	< 0.5	0.6	4.5	1.7	0.42
North side of Calkins Lake; ungrazed field east of water intake station. (NW 1/4 Sec. 26, T.2S., R.69W)	7	< 0.5	0.4	4.0	2.8	0.07
Grazed area just to the southeast of the road culvert conveying Woman Creek under Indiana Street. (NW 1/4 Sec. 18, T.2S., R.69W)	16	< 0.5	1.6	5.4	1.0	2.42

(a) Uranium in µg/gram

Discussion

Surface contamination of land surfaces in the vicinity of the Rocky Flats Plant has occurred as the result of uncontrolled releases of plutonium. The special soil sampling program conducted by the State of Colorado in February 1970 showed plutonium concentrations in excess of that attributable to global fallout at radial distances up to three miles from the plant boundary. The two sectors (refer to Appendix B) immediately adjacent to the plant showed the maximum topsoil concentrations of plutonium-239; 2.5 and 11 pCi per gram dry weight. It was the State's conclusion that the primary source of contamination was the "incident" involving the leakage of oil and not the May 11, 1969, fire. In contrast, the report of the Colorado Committee for Environmental Information strongly suggested the May 11 fire as the primary causative factor. As far as the public health implications of the land contamination are concerned, the source, whether it be the incident involving the fire or the oil leakage, is not really revelant.

It is extremely difficult to attempt to relate plutonium concentrations in unconsolidated topsoil to possible or potential levels of human exposure. Deposited in-place, there is no significant health risk. External exposure will not occur because of the very limited range of the emitted alpha radiation. Similarly, transfer through the food chain (for example, soil to vegetation to wild game or grazing stock) will be of no consequence since plutonium is absorbed by plants growing on contaminated soil to only an infinitesimal degree.[7] However, resuspension and wind transport of contaminated particulates - apparently a likely condition for the Rocky Flats area - may lead to inhalation and resultant radiation dose. For discussion of

this latter pathway and the potential health risk it represents, the interested reader is referred to the State of Colorado's analysis (Appendix B) and the report of the Colorado Committee for Environmental Information.

The discharge of liquid radioactive wastes was observed to have only a minor effect on dissolved radioactivity concentrations in Walnut Creek, at least during the two-day sampling period. The dissolved concentrations of uranium and plutonium were just slightly in excess of baseline values and, in each case, several orders of magnitude less than the corresponding effluent concentration specified in AEC regulation 10CFR20, and the limiting concentration in water for the general public, as recommended by the National Committee on Radiation Protection and the International Commission on Radiological Protection (Table IX). Unfortunately, the degree to which the specific grab sample results are representative of average or long-term conditions can only be determined by additional monitoring. The effluent to the south fork of Walnut Creek has been continuously sampled by plant personnel and the State of Colorado has been monitoring WalnutCreek at Indiana Street. The analysis of these samples usually involves only total gross alpha determinations, the results of which are not directly comparable with dissolved radioactivity data. However, the effluent concentration of total gross alpha activity stated to be typical, 15 pCi/l, indicates that specific findings for the levels of dissolved uranium and plutonium may actually be representative of average water quality conditions in the creek.

The most demonstrable effect of liquid radioactive waste discharges was the accumulation of plutonium in bottom sediment throughout the entire

Table IX

Limiting Concentrations for Plutonium-239 and Uranium

Agency	Radionuclide	Dissolved Concentration Limit	Applicability
Atomic Energy Commission	Plutonium-239	5000 pCi/l	Effluent at point of entry into the unrestricted area.
	Uranium-238	120 mg/l	
National Committee on Radiation Protection	Plutonium-239	1700 pCi/l[(a)]	Exposure of the general public
International Commission on Radiological Protection.	Uranium-238	40 mg/l (NCRP)[(a)]	Exposure of the general public
		600 µg/l (ICRP)[(a)]	

(a) 1/30th of the maximum permissible concentration for continuous occupational exposure (168-hour week).

length of Walnut Creek. Representing accumulation and deposition over an undetermined period of time, the February 1970 sediment samples contained plutonium in concentrations as high as 3.5 pCi/gram (State of Colorado data showed a maximum of about 20 pCi/gram). Such accumulation occurs by two processes: 1) deposition of plutonium associated with suspended material in the effluent, and 2) transfer of plutonium from the dissolved (ionic) state by chemical precipitation and/or adsorption. From the standpoint of environmental significance as regards human exposure, plutonium deposited in Walnut Creek is of no consequence. However, these contaminated sediments are periodically flushed out of the creek and deposited in Great Western Reservoir wherein there exists availability for incorporation and accumulation in the aquatic web. The limited available information on the movement of plutonium in the environment indicates that biological accumulation as well as dissolution of plutonium from the sediment will be negligible. Nonetheless, the previously mentioned study of September 1970 was conducted to ensure that these predictions are indeed valid.

In contrast to the situation in the south fork and main stem of Walnut Creek, the sources of elevated plutonium concentrations in samples from the middle fork of Walnut Creek, Woman Creek, and shallow shoreline areas of Great Western Reservoir and Mower Reservoir were considered to be air transport and surface runoff of plutonium-contaminated soil. As noted in the preceding paragraph, the plutonium deposited in these areas is probably biologically and chemically inert.

Increased levels of dissolved radioactivity attributable to plant releases were not observed in any of the lakes and reservoirs sampled. This finding is generally supported by the long-term monitoring data compiled by plant personnel for several reservoirs in the plant environs, including Great Western Reservoir and Standley Lake. However, since the plant monitoring program is limited to total gross alpha determinations, detection of small increases in plutonium concentrations, such as those observed in Walnut Creek, would not be expected. It is also interesting to note that the concentrations of dissolved uranium in the grab water samples from Great Western Reservoir and Standley Lake almost totally account for the corresponding reported levels of total gross alpha concentrations. The radiation dose associated with the utilization of Great Western Reservoir, Standley Lake, and Calkins Lake as sources of public water supply is negligible. Without taking credit for possible concentration reductions achieved by water treatment, the dose received by members of each population group served is less than one one-hundred-thousandth (10^{-5}) of the dose limit for individuals.

The apparent effectiveness of the Broomfield water treatment process for reducing uranium and plutonium concentrations - raw versus finished water - was indicated by the radioactivity results for the sample of settled alum sludge. On a dry weight basis, the plutonium and uranium concentrations in the sludge were comparable to the plutonium concentrations and about 40X the uranium concentrations in Walnut Creek sediment. Disposal of the sludge is to a small retention pond adjacent to the water treatment plant.

Conclusions

Monitoring data do not indicate any public health hazard associated with the routine discharge of liquid radioactive wastes to Walnut Creek. There has been no measurable degradation of plant origin in the radiological water quality of Great Western Reservoir, the source of public supply for the City of Broomfield. This reflects the general adequacy of the liquid waste management program carried on at the Rocky Flats Plant. In this respect, additional abatement requirements are not indicated at this time.

Recommendations

In order to obtain a more comprehensive documentation of the radioactivity discharged to the environment via the liquid radioactive waste treatment and disposal system and the ultimate distribution thereafter, the Water Quality Office has the following recommendations:

1. Routine monitoring of radioactivity levels in water in the effluent to Walnut Creek, Walnut Creek (at Indiana Street culvert) and Great Western Reservoir should include determinations of suspended and dissolved radioactivity; not total radioactivity in the unfiltered sample.

2. In addition to gross alpha activity determinations, specific analyses should be conducted for plutonium-239 and uranium.

3. At least annually, preferably semi-annually, levels of plutonium in the various trophic levels of the aquatic populations inhabiting Great Western Reservoir and Standley Lake should be determined.

4. Semi-annual monitoring reports should be expanded to include data on effluent flow and radioactivity concentrations in the effluent to the south fork of Walnut Creek. Sufficient data should be presented to permit the calculation of at least the monthly amounts (curies) of plutonium and uranium (suspended and dissolved) discharged to the creek.

Any recurrence of "incidents" resulting in off-site contamination cannot be tolerated; irrespective of the associated level of off-site contamination - negligible or of potential public health significance. Whatever preventive measures and/or facilities are considered necessary for the absolute prevention of incidents resulting in the venting of radioactive materials to the atmosphere must be implemented and/or installed. Remoteness of location is not a safety factor in this particular case, and this must be reflected accordingly in the operational aspects and safety program of the plant.

Appendix A

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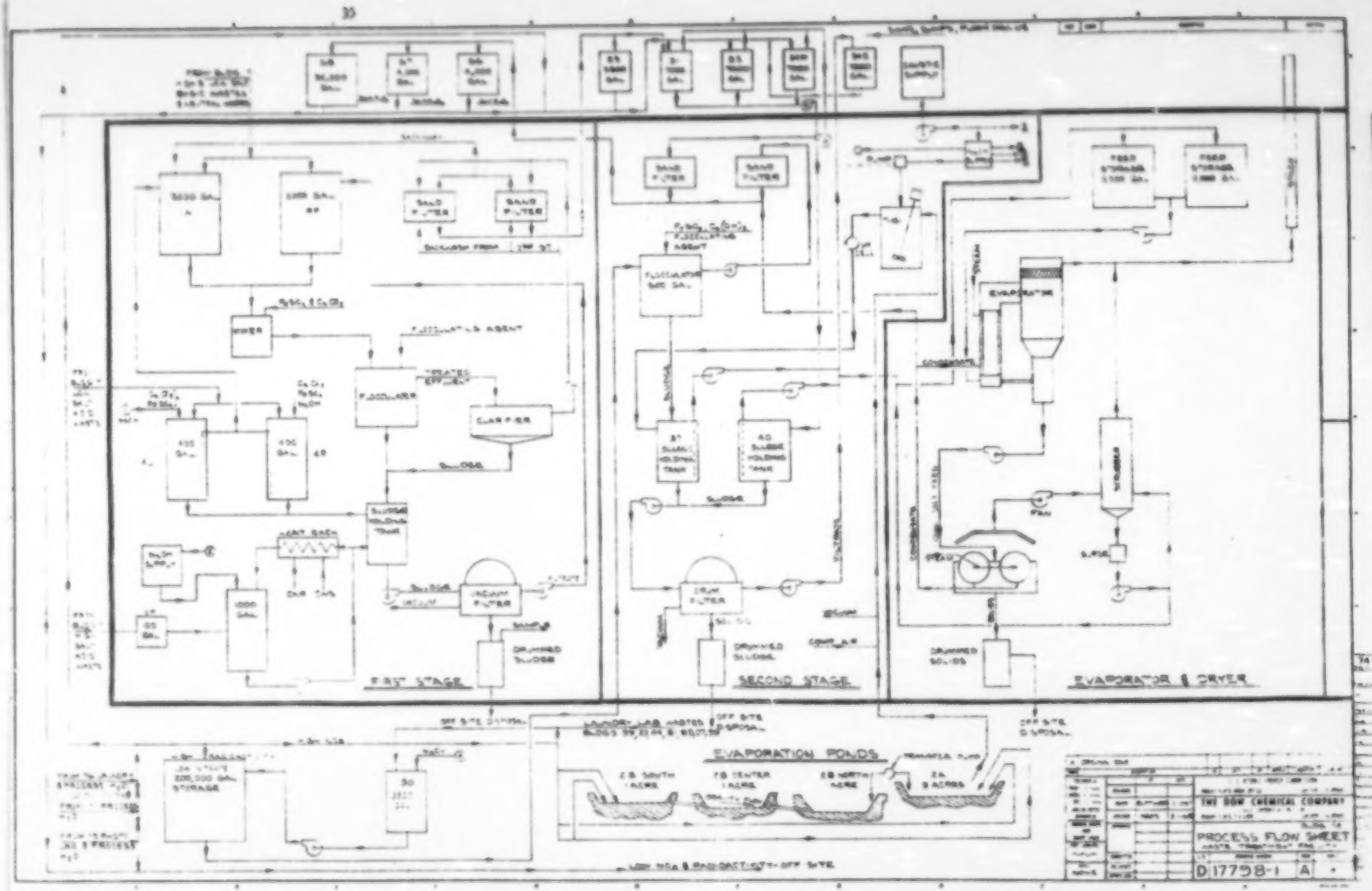

Appendix B

37 Rec'd. 6/16/70

COLORADO DEPARTMENT OF HEALTH

4210 EAST 11TH AVENUE · DENVER, COLORADO 80220 · PHONE 388-6111

R. L. GLEERE, M.D., M.P.H., DIRECTOR

June 9, 1970

Enclosed are copies of the latest surveillance information on the Rocky Flats Plant. You will note the soil sample results clearly indicate the distribution of the ^{239}Pu contamination.

Before briefly describing the soil analysis results, it might be well to first explain the sampling technique used.

The U.S.P.H.S. obligated themselves to analyze 25 total samples for ^{239}Pu and ^{90}Sr content. This was because the plutonium analysis, in particular, is extremely time consuming and they, of course, have other commitments for other surveillance activities. To take full advantage of this limited number of analyses, it was decided that a composite sampling program was indicated. As you can see by the map attached to the soil analysis results, the area around the Rocky Flats Plant was divided into 13 sectors. These sectors were located at 1, 3 and 6 mile distances from the plant boundary. Twenty-five soil samples were collected in each sector with 20% or 5 separate samples collected additionally in each sector and retained for future reference. Each location sampled is approximated on the map. The number of composite soil samples in the designated area totaled 325. Composite sediment samples of significant water bodies totaled 190. The soil samples collected were of the top 1/8" of undisturbed soil which would be indicative of the most severe health hazard in regard to re-suspension from the soil to the air.

It is interesting to note the similarity of results of the 75 background samples collected in Limon, Loveland and Penrose areas using the same composite sampling technique as described above. Although we plan to expand the number of background sampling areas, we anticipate that the present samples accurately describe the ^{239}Pu "background" levels on the Eastern Slope. These levels are due almost entirely from fallout from past atmospheric nuclear testing.

Also worthy of note, are the results of the ^{90}Sr analyses and the $^{239}Pu/^{90}Sr$ ratios for sector soil samples, "background" soil samples and sediments. These results would indicate that the ^{239}Pu results alone are the best indicator of the effect that the Rocky Flats Plant has had on the environment.

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It is our conclusion that no public health hazard now exists from past releases from the Rocky Flats Plant. It would be impossible, however, to estimate any hazard which existed in the past. The highest concentrations were found adjacent to the plant at the eastern boundary. This area is directly downwind from the area that the leakage of plutonium-contaminated oil and subsequent soil contamination occurred sometime during the period of 1955 through 1967. The main oil spill area was covered with asphalt in September, 1969 and an apron of 3" of base course material was completed around this area in March, 1970. The plutonium levels in the soils in this area were high and the material was carried downwind. The elevated ^{239}Pu levels in Sectors 1, 2, 6 and 7 are primarily the result of this "incident."

Sector 2, which has the highest concentration of ^{239}Pu, can best be described as a non-populated area, access to which is not controlled. In a paper by R. L. Kathren (1968), which was an extensive review of work done on plutonium contamination, "interim acceptable surface contamination levels for environmental PuO_2" are proposed. Based on dose to pulmonary lymph nodes, the following would be acceptable levels for occupancy by the general public:

Urban areas	10 dpm/cm^2
Rural areas	100 dpm/cm^2

ICRP Publication 14 (1969) states that the dose limit for plutonium on the basis of risk to lymphoid tissue is not warranted. Adjustment of the above proposed acceptable levels would be upward by a factor of 2 or more. Based on the conservative numerical terms used by Kathren, the level identified in Sector 2 (8 dpm/cm^2) is safe (acceptable) by at least a factor of 25. If the entire 13-sector area (0.3 dpm/cm^2) is used, the factor would range from 70 to 700 depending on whether the entire area would be considered as urban or rural, respectively. Less conservative limits would, of course, provide a greater factor, and several of these were reviewed.

Extrapolation of the data indicates that the total ^{239}Pu soil contamination of the environment around the Rocky Flats Plant attributable to the plant approximates 0.3 Curie (4.9 grams ^{239}Pu) at the present time, 57% of which is located in Sector 2.

Because hazard analysis based on soil data utilizes arbitrary re-suspension and "air concentration half-life" factors, the only proper method to thoroughly evaluate the situation is by air surveillance.

The Department's plans are to continue, and in some cases increase, air surveillance activities downwind from both the contaminated area and the plant in general, and to work with Rocky Flats personnel in an effort to more fully identify and control any potential contaminant releases from the plant. Samples from Sector 2 will be collected and analyzed to determine the long-term characteristics of ^{239}Pu in soils,

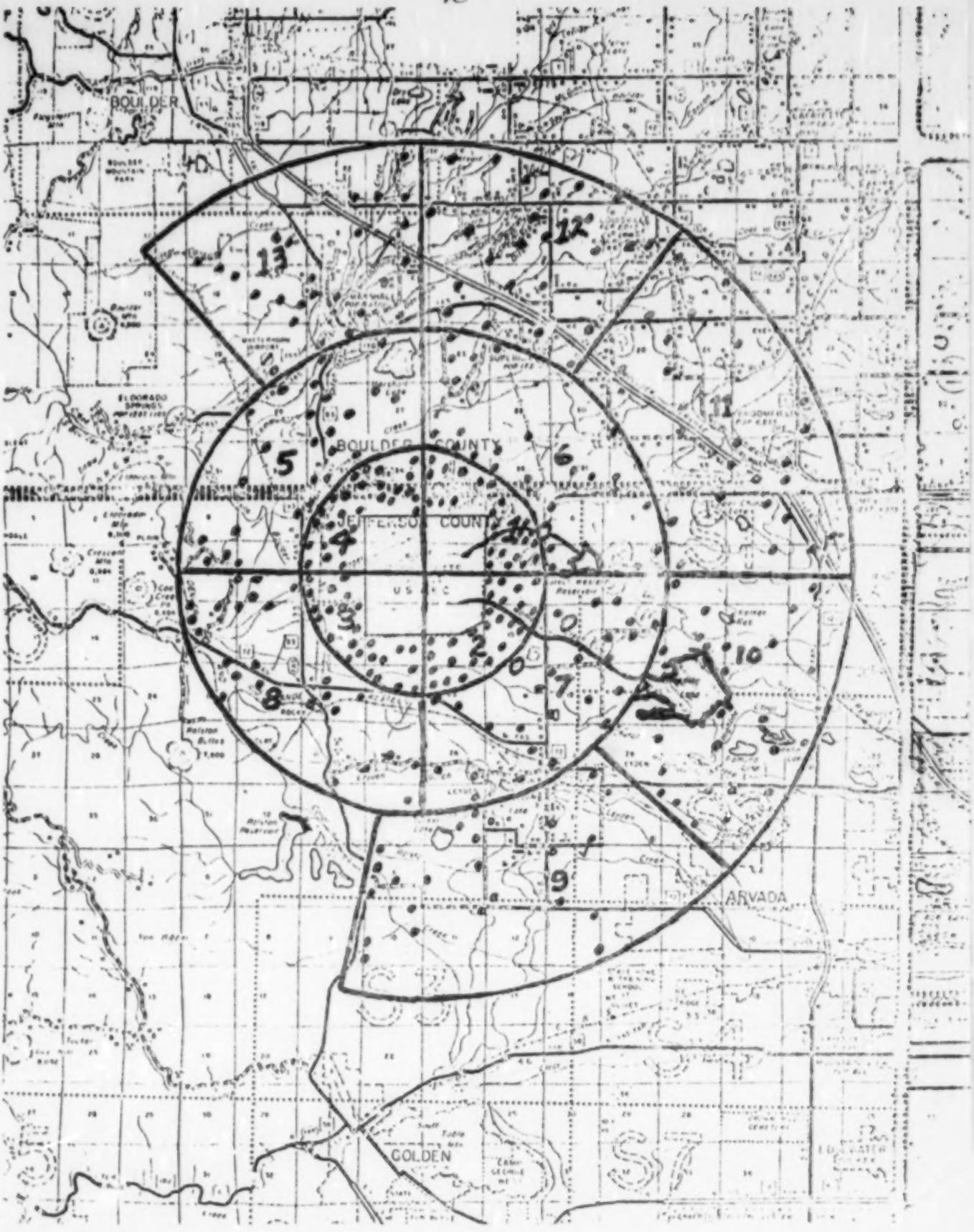
and of course as previously mentioned, an expanded effort will be made to establish an existing ^{239}Pu "background" for Colorado. With the provision of additional funds, a higher percentage of samples (air, water and soils) will be analyzed for ^{239}Pu, thereby giving the Department an independent capability for hazard analysis, and definition of plant releases.

If you have any questions regarding this matter, please let us know.

Sincerely,

P. W. Jacoe, Director
Division of Air, Occupational,
and Radiation Hygiene

PWJ/md
Enclosures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U.S.P.H.S. - SWRHL Analysis
Soil & Sediment Sampling Results

SOILS:

Backgrounds Sample Date	Location	dpm/g dry soil ^{239}Pu	^{90}Sr	Ratio Pu/Sr
2/18/70	Limon, Colorado	0.13	2.9	0.045
2/18/70	Loveland, Colorado	0.11	1.8	0.061
2/18/70	Penrose, Colorado	0.11	1.6	0.069
Samples				
2/18/70	Area 1	5.55	2.4	2.31
2/19/70	Area 2	24.4	2.4	10.2
2/18/70	Area 3	0.29	3.3	0.088
2/18/70	Area 4	0.31	3.6	0.086
2/18/70	Area 5	0.24	15.8	0.015
2/18/70	Area 6	1.00	1.6	0.625
2/19/70	Area 7	1.02	1.3	0.785
2/18/70	Area 8	0.04	1.1	0.036
2/18/70	Area 9	0.02	< 0.4	0.050
2/17/70	Area 10	0.38	< 0.4	0.950
2/18/70	Area 11	0.07	0.9	0.078
2/17/70	Area 12	< 0.02	0.9	0.022
2/19/70	Area 13	0.04	1.1	0.036
SEDIMENTS:				
2/18/70	Upper South Walnut Creek	46.6	< 0.4	--
2/18/70	Walnut Creek	109.0	< 0.4	--
2/18/70	Pond Walnut Creek and Indiana	28.9	< 0.4	--
2/18/70	Great Western Reservoir	0.53	0.4	--
2/18/70	Woman Creek	2.18	0.4	--
2/18/70	Mower Reservoir	0.89	< 0.4	--
2/18/70	Standley Lake	0.07	< 0.4	--
2/18/70	Pond West of Indiana and 96th	0.53	lost	--
2/25/70	Ralston Reservoir inlet	0.40	0.4	--
2/25/70	Ralston Reservoir high water mark at inlet	0.02	< 0.4	--
2/25/70	Ralston Reservoir 100 yds. from inlet	0.16	< 0.4	--

Notes:

The soil was analyzed for strontium by acid leach and ion exchange and for plutonium by total dissolution, ion exchange and electroplating.

The values that appear high were rechecked and th values confirmed.

All Strontium 89 concentrations were found to be less than 1.1 dpm/gm of dry soil.

AJH:vam 5/25/70

Total ^{239}Pu Activity By Sector

Sector	^{239}Pu dpm/g dry soil	^{239}Pu dpm/cm^2	Area mi^2	Area cm^2	$dpm \times 10^{10}$	Ci
1	5.55	1.78	2.1	5.4×10^{10}	9.59	0.0432
2	24.4	7.81	2.2	5.7×10^{10}	44.5	0.2005
3	0.29	0.09	2.1	5.4×10^{10}	0.501	0.0023
4	0.31	0.10	2.1	5.4×10^{10}	0.536	0.0024
5	0.24	0.08	9.4	2.4×10^{11}	1.84	0.0083
6	1.00	0.32	9.4	2.4×10^{11}	7.68	0.0346
7	1.02	0.33	9.4	2.4×10^{11}	7.83	0.0353
8	0.04	0.01	9.4	2.4×10^{11}	0.307	0.0014
9	0.02	0.01	16.1	4.2×10^{11}	0.269	0.0012
10	0.38	0.12	13.0	3.4×10^{11}	4.13	0.0186
11	0.07	0.02	13.0	3.4×10^{11}	0.762	0.0034
12	< 0.02	< 0.01	13.0	3.4×10^{11}	0.218	0.0010
13	0.04	0.01	13.0	3.4×10^{11}	0.435	0.0020
Totals	-	0.27	114.2	296×10^{10}	78.6	0.354
Bkg	0.12	0.04	-	-	11.4	0.051
Net (Dow soil contamination contribution)						0.30

0.30 Ci ^{239}Pu x 16.2 gms ^{239}Pu/Ci ^{239}Pu = 4.9 gms ^{239}Pu

Appendix C

Analytical Methods

The analytical procedures used in this study are taken from the published literature with adaptation or modifications made in the pretreatment of the sample to fit the published analytical procedure. The limit of detection is that limit which is defined in the National Bureau of Standards Handbook 86, page 26.

Analyses for water were done on the dissolved portion only; that is, the portion which passes through a 0.45 μ porosity millipore filter. Soils and sediment samples were dried at 105° - 110°C, ground and sieved to 100 mesh.

Gross Alpha Analyses

One hundred milligrams of dissolved solids or sediment were transferred to a stainless steel planchet, distributed evenly, fixed by a dilute lucite solution, and alpha counted in an internal proportional counter. The background count rate was nominally 0.1 cpm and the detection efficiency, based on a radium-226 standard, was nominally 30%. The limit of detection for water samples varied with dissolved solids concentration, ranging from 1 - 4 pCi/l, and for sediment and soil samples, 1.4 pCi/g.

Total Alpha Radium

The procedure used was that of Goldin,[8] with modifications made for the pretreatment of sediment and soil samples. This modification consisted

of fusion of the sample using the flux described by Rushing.[9] The limit of detection, based on a radium-226 calibration standard, is 0.1 pCi/g and 0.1 pCi/l, respectively, for sediment and water samples.

Uranium

The procedure used for water analysis was essentially that of Edwards.[10] Soils and sediments were acid leached and the uranium extracted into ethyl acetate from an acidified magnesium nitrate solution. Uranium is determined fluorometrically[11] using a standard addition technique rather than by alpha spectroscopy. Limits of detection (10% full scale, using 0.05 µg standard) are 0.3 µg/l and 0.3 µg/g for water and sediment, respectively.

Strontium-90

The procedure used was taken from Krieger et al.[12] and Velten.[13] Pretreatment of sediment and soil samples consisted of acid leaching with 6N HCl, using a Soxhlet extractor. Limits of detection are 0.1 pCi/g and 0.3 pCi/l for sediment and water, respectively.

Plutonium

Pretreatment of sediment and soil samples consisted of acid leaching with 6N HCl,[14] using a Soxhlet extractor, and ultimate conversion to the nitrates by repetitive evaporation with nitric acid. Water samples are evaporated to dryness and treated with nitric acid. Plutonium is oxidized and extracted from 4N nitric acid into 0.1 m tri-n-octylphosphine oxide.[15] Plutonium is reduced and back extracted and counted in an internal proportional counter. Limits of detection are 0.02 pCi/g and 0.02 pCi/l for sediment and water, respectively.

Tritium

This procedure is taken from Krieger et al,[12] with the exception that the volume ratio of scintillator to sample is increased to 5:1. Limit of detection is 400 pCi/l.

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